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ON THE OPTIMUM DESIGN OF CATHODE FOLLOWERS

by

L. M. VALLESE

Report R-390-54, PIB-323

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ABSTRACT

An analytical procedure to obtain a preliminary design of large signal cathode follower amplifiers is described. A-C amplifiers with conductive and inductive cathode admittance as well as d-c amplifiers are considered. The conditions of optimization of the design for maximum power or voltage output are discussed.

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Introduction

Cathode followers find wide application in modern Electronics because of their simple structure, fairly distortionless operation and low output impedance. Their design for small signal amplification is easy; for large signal amplification an added complication is introduced with the requirement that the distortion-free driving range of the control grid be utilized fully. Usually this problem is solved graphically, but the procedure is cumbersome and of limited application. Its usefulness can be greatly enhanced if it is used merely to check and improve an approximate preliminary design obtained analytically. The derivation of such a preliminary design is the object of this report. For this purpose the family of characteristics of the tube will be represented by a bilinear relationship

$$i_b = g_p\,(e_b - v_{bk}) = g_p\,(e_b + \mu e_{ck} - V_o') \tag{1}$$

which corresponds to a set of straight lines (Fig. MRI-14276-a) characterized by their slope g_p and their intercept V_{bk} with the $i_b = 0$ axis (in particular V_o' and V_{bk}' are respectively the intercepts corresponding to $E_{ck} = 0$ and $E_{ck} = -0.5$ V). The main purpose of the design consists in determining the values of E_Q, I_Q so that the grid-to-cathode voltage may be varied between -0.5 V and a value corresponding to a minimum current I_{bm}. In addition the design may be optimized with respect to the power and voltage output, plate dissipation, etc. We shall discuss separately the cases of a-c and d-c amplifiers and shall show that the design of the a-c amplifiers is subject to less restrictions than that of d-c amplifiers. The cathode admittance of a-c amplifiers can be either a conductance G_K or a (small) inductive susceptance $1/j\omega L = -jB_K$, while the cathode admittance of d-c amplifiers must be a conductance G_K.

I. A-C Cathode Followers with Conductive Cathode Admittance

The circuit diagram of a typical a-c cathode follower with conductive cathode admittance is indicated in Fig. MRI-14276-b. We shall disregard high and low frequency effects and limit our analysis to the mid-frequency range. For this purpose the interelectrode and coupling capacitances will be neglected, and the design will be limited to the determination of the quantities G_K, G_L, E_{bb}, E_o, E_s, $(E_{ck})_Q$, E_Q, I_Q. The interpretation of these symbols is clear from Fig. MRI-14276-b; we shall only point out that E_o and E_s are peak rather than rms values.

The following limitations must be satisfied:

$$\left.\begin{aligned} &E_{ck} \leq E_{ck\ max} = -0.5\ V \\ &I_{bm} \leq i_b \leq I_{k\ max} \\ &E_{bb} \leq E_{bb\ max} \\ &E_Q\ I_Q \leq P_{p\ max} \end{aligned}\right\} \quad (2)$$

The last of conditions (2) applies for zero signal dissipation; it could be replaced with the less restrictive condition $E_Q I_Q - P_L \leq P_{pmax}$, if the power output P_L were a constant.

The following relationships can be used for the analysis:

$$2I_Q = I_{bm} + I_{bM} \quad (3)$$

$$I_{bM} = g_p\ (E_Q - E_o - V'_{bk}) = g_p\ (e_{bm} - V'_{bk}) \quad (4)$$

$$I_Q = G_k\ (E_{bb} - E_Q) = I_{bm} + E_o\ (G_k + G_L) \quad (5)$$

$$E_Q = e_{bm} + E_o = V'_{bk} + \frac{I_{bM}}{g_p} + E_o \quad (6)$$

$$E_{bb} = E_Q + I_Q/G_k \quad (7)$$

$$(E_{ck})_Q = \frac{1}{\mu}\ (V'_o - V_{bk}) = \frac{1}{\mu}\ (V'_o - E_Q + I_Q/g_p) \quad (8)$$

$$E_s = E_c + (E_{ck})_Q - 0.5 \quad (9)$$

$$e_{bm} = V'_{bk} + \left[I_{bm} + 2\ E_o\ (G_k + G_L) \right] /g_p \quad (10)$$

By elimination of E_Q, I_Q from (3),(4),(5) one has

$$G_k^2 - \frac{g_p}{2E_o} \left[E_{bb} - 2E_o (1 + \frac{G_L}{g_p}) - \frac{I_{bm}}{g_p} - V'_{bk} \right] G_k + \frac{g_p}{2}\ (G_L + \frac{I_{bm}}{E_o}) = 0 \quad (11)$$

which is a relationship among E_{bb}, E_o, G_k, G_L and can be used to determine one of these quantities when the other three are given. One has:

$$G_L = \frac{g_p\left[E_{bb} - V'_{bk} - 2E_o\right]G_k - 2E_oG_k^{\,2} - I_{bm}(g_p + G_k)}{E_o\,(2\,G_k + g_p)} \tag{12}$$

or

$$E_o = \frac{g_p(E_{bb} - V'_{bk})\,G_k - (g_p + G_k)\,I_{bm}}{2\,G_k(G_k + g_p) + (g_p + 2\,G_k)\,G_L} \tag{13}$$

or

$$G_k = \frac{g_p}{4E_o}\left[E_{bb} - 2E_o\left(1 + \frac{G_L}{g_p}\right) - \frac{I_{bm}}{g_p} - V'_{bk}\right] \pm \sqrt{\frac{g_p^2}{16E_o^2}\left[\quad\right]^2 - \frac{g_p}{2}\left(G_L + \frac{I_{bm}}{E_o}\right)} \tag{14}$$

and finally

$$E_{bb} = V'_{bk} + I_{bm}\left(\frac{1}{G_k} + \frac{1}{g_p}\right) + 2E_o\left(1 + \frac{G_L}{2G_k} + \frac{G_k + G_L}{g_p}\right) \tag{15}$$

Two other important relations are:

$$I_{bM} = I_{bm} + 2E_o(G_k + G_L) = \frac{2(G_k + G_L)g_p\,G_k(E_{bb} - V'_{bk}) - g_pG_LI_{bm}}{2(g_p + G_k)(G_k + G_L) - g_p\,G_L} \tag{16}$$

and

$$P_p = E_QI_Q = \left[E_o\left(1 + \frac{2(G_k + G_L)}{g_p}\right) + V'_{bk} + \frac{I_{bm}}{g_p}\right]\left[I_{bm} + E_o(G_k + G_L)\right] =$$

$$= \left[E_{bb} - \frac{1}{G_k}\left(I_{bm} + (G_k + G_L)E_o\right)\right]\left[I_{bm} + E_o\,(G_k + G_L)\right] \tag{17}$$

We shall now proceed to consider a number of specific problems that can occur in practice, and derive the optimum approximate solution. In particular, numerical design values of somewhat academic interest will be computed, assuming that the tube employed is the 6J5, whose plate characteristics are shown in Fig. MRI-14277. The latter ones are linearized assuming $g_p = 1/7600 = 1.32 \times 10^{-4}$ mhos, $V_o' = 30V$, $V_{bk}' = 40$ V, $I_{bm} = 0.5$ mA, $\mu = 20$, $I_{kM} = 20$ mA, $E_{bbM} = 300$ V, $P_{pmax} = 2.5$ w.

Design No. 1 - Given the tube, G_k, G_L, E_o find the minimum necessary value of E_{bb}.

One uses formula (15), then checks that the values of E_{bb}, I_{bM}, P_p are less than the limiting values (2). Finally one computes $(E_{ck})_Q$, E_{GG} and E_s.

For example assume that the tube is a 6J5 and that $G_k = 4 \times 10^{-4}$ mhos, $G_L = 10^{-3}$ mhos, $E_o = 5$ V. There follows:

$$E_{bb} = 40 + 0.5\times10^{-3}(2500 + 7600) + 10\ (12.85) = 173.5\ \text{V}$$

The check with respect to the limit performance of the tube provides

$$I_{bM} = 14.5\ \text{mA}$$

$$I_Q = 7.5\ \text{mA}$$

$$E_Q = 116\ \text{V}$$

$$P_p = 0.87\ \text{w}$$

Furthermore

$$(E_{ck})_Q = \frac{1}{20}\left[30-116+57\right] = -1.45\ \text{V}$$

$$E_{GG} = E_Q + (E_{ck})_Q = 114.5\ \text{V}$$

$$E_s = 5 + 1.45 - 0.5 = 5.95\ \text{V}$$

$$K = \frac{E_o}{E_s} = 0.84$$

Design No. 2 - Given the tube, G_k, G_L, find E_{bb} for max. E_o permissible.

Since E_o increases linearly with E_{bb}, we shall merely investigate the maximum value of E_o. With respect to the current limitation this is (eq. 16)

$$E_o' = \frac{I_{kM} - I_{bm}}{2(G_k + G_L)} \tag{18}$$

With respect to the power limitation one has from eq. 17

$$E_o'' = -\alpha + \sqrt{\alpha^2 + \beta} \tag{19}$$

where

$$\alpha = \frac{\left[g_p + 2(G_k+G_L)\right] I_{bm} + (G_k+G_L)(g_p V_{bk}' + I_{bm})}{2(G_k+G_L)\left[g_p + 2\,(G_k + G_L)\right]}$$

$$\beta = \frac{g_p\, P_{pmax} - (g_p\, V_{bk}' + I_{bm})\, I_{bm}}{(G_k + G_L)(g_p + 2(G_k + G_L))}$$

The lower of the values (18), (19) is the maximum permissible E_o. Correspondingly E_{bb} is obtained from eq. 15. For example, for a 6J5 with $G_k = 4 \times 10^{-4}$ mhos, $G_L = 10^{-3}$ mhos one has

$$E_o' = 7.3\ \text{V}\ ,\quad E_o'' = 7.83\ \text{V}$$

The maximum permissible value E_o is 7.3 V and the corresponding value of E_{bb} is 232.5 V.

Design No. 3 - Given the tube, G_L, E_o, E_{bb} find G_k.

One uses eq. (14) which provides two solutions for G_k. These are checked with respect to conditions (2). Assuming that both G_k values are permissible, the final choice will be determined by considerations of the plate power dissipation, peak cathode current, output admittance.

For example for a 6J5, given $G_L = 10^{-3}$ mhos, $E_o = 5V$, $E_{bb} = 173$ V, the corresponding values of G_k are

$$G_k' = 0.4 \times 10^{-3} \text{ mhos} \qquad G_k'' = 0.177 \times 10^{-3} \text{ mhos} \tag{20}$$

Incidentally, if $E_{bb} = 200$ V the values of G_k are

$$G_k' = 0.837 \times 10^{-3} \text{ mhos} \qquad G_k'' = 0.083 \times 10^{-3} \text{ mhos}.$$

In connection with the values (20) one finds

$$I_{bM}' = 14.5 \text{ mA} \qquad I_{bM}'' = 12.27 \text{ mA}$$

$$E_Q' = 116 \text{ V} \qquad E_Q'' = 98.2 \text{ V}$$

$$P_p' = 0.87 \text{ w} \qquad P_p'' = 0.625 \text{ w}$$

Design No. 4 - Given the tube, G_L, E_{bb} find G_k for max. E_o. From eq. (13), letting $\frac{dE_o}{dG_k} = 0$, one has

$$G_k = \frac{g_p I_{bm}}{g_p(E_{bb}-V_{bk}')-I_{bm}} + \sqrt{\frac{g_p^2 I_{bm}^2}{[g_p(E_{bb}-V_{bk}')-I_{bm}]^2} + \frac{g_p}{2}\left(G_L + \frac{2(g_p+G_L)I_{bm}}{g_p(E_{bb}-V_{bk}')-I_{bm}}\right)} \tag{21}$$

For example, letting $G_L = 10^{-3}$ mhos, $E_{bb} = 173$ V, one has for the 6J5

$$G_k = 2.61 \times 10^{-4} \text{ mhos}$$

and from eq. (13)

$$E_o = 5.09 \text{ V}$$

For given G_L and E_{bb} it is of interest to compute the limit values of G_k for which respectively $I_{bM} = I_{kM}$ or $P_p = P_{pmax}$. By application of eq. (13) these provide the corresponding limit values of E_o.

For the condition $I_{bM} = I_{kM}$ one has from eq. 16, solving for G_k

$$G_k = - b + \sqrt{b^2 - c} \qquad (22)$$

where

$$b = - \frac{G_L}{2} + \frac{g_p I_{kM}}{2 g_p(E_{bb}-V'_{bk}) - 2I_{kM}}$$

$$c = \frac{g_p G_L [I_{kM} - I_{bm}]}{2 g_p(E_{bb}-V'_{bk}) - 2 I_{kM}}$$

In particular, if $G_L = 0$, eq. (22) reduces to

$$G_k = \frac{1}{\frac{E_{bb}-V'_{bk}}{I_{kM}} - \frac{1}{g_p}} \qquad (23)$$

Similarly eqs. (13) and (17) provide the limit values G_k and E_o for which $P_p = P_{pmax}$. Since these eqs. are of the fifth degree in G_k, they should be solved by trial and error method.

Design No. 5 - Given the tube, E_{bb}, find G_k and G_L for max. output power $P_L = G_L E_o^2/2$. This design may be considered of academic interest, since cathode followers for power amplification are usually made with inductive rather than conductive cathode admittance.

According to eq. 13 one has

$$P_L = \frac{G_L}{2} \left[\frac{g_p(E_{bb}-V'_{bk})G_k-(g_p + G_k) I_{bm}}{2 G_k (G_k + g_p) + (g_p+2G_k)G_L} \right]^2 \qquad (24)$$

which is a function of E_{bb}, G_k, G_L. If either G_k or G_L are given, the optimum value of the conductances G_L or G_k is determined respectively with the condition

$$\frac{dP_L}{dG_L} = 0 \quad \text{or} \quad \frac{dP_L}{dG_k} = 0 \tag{25}$$

If G_k and G_L are both indetermined, the latter two equations must be solved simultaneously.

From eq. 25 there follows

$$G_L\,(2G_k + g_p) - 2G_k(G_k + g_p) = 0 \tag{26}$$

$$G_k^2 + \frac{g_p\, I_{bm}\, G_k}{g_p(E_{bb}-V'_{bk}) - I_{bm}} - \frac{g_p}{2}\left[G_L + \frac{2(g_p + G_L)\, I_{bm}}{g_p(E_{bb}-V'_{bk}) - I_{bm}}\right] = 0$$

In particular the last equation for $I_{bm} = 0$ simplifies as follows

$$2\,G_k^2 - g_p\,G_L = 0 \tag{27}$$

Therefore, if G_k is given, the optimum value of G_L is

$$G_L = 2\,G_k\,\frac{G_k + g_p}{2G_k + g_p} \tag{28}$$

If G_L is given the optimum value of G_k is computed by means of eq. 21 and in particular for $I_{bm} = 0$ one has

$$G_k = \sqrt{g_p\,G_L/2} \tag{29}$$

Finally, if both G_k and G_L are indetermined, their optimum values are respectively

$$G_k = g_p/\sqrt{2}\,, \quad G_L = g_p \tag{30}$$

Correspondingly the peak power output is

$$(P_L)_{peak} = \frac{0.0215}{2} g_p \left[E_{bb} - V'_{bk}\right]^2$$

For example, with a 6J5 with $E_{bb} = 200V$, $(P_L)_{peak}$ is 0.363 w. In Table I the quantity $2P_L/g_p\ (E_{bb} - V'_{bk})^2$ has been computed for various values of G_k/g_p, G_L/g_p near the optimum values (30).

Table I - Values of $2P_L/\left[g_p\ (E_{bb} - V'_{bk})^2\right]$

G_k \ G_L	$g_p/\sqrt{2}$	g_p	$\sqrt{2}\ g_p$
$g_p/2$	0.0208	0.0204	0.0188
$g_p/\sqrt{2}$	0.0208	0.0215	0.0208
g_p	0.0188	0.0204	0.0208

II. A-C Cathode Followers with Inductive Cathode Admittance

The circuit diagram of a typical cathode follower with inductive cathode admittance is indicated in Fig. MRI-14278-a. It is assumed that $jB_k = 1/j\omega L$ is negligible; in addition, high and low frequency effects are neglected.

The limitations of the design are expressed by equations (2), where $E_Q = E_{bb}$. The design itself is much simplified in the present case and reduces to finding I_Q, since E_Q is fixed. The design equations are

$$I_Q = I_{bm} + G_L E_o \tag{31.1}$$

$$I_{bM} = g_p (E_{bb} - V'_{bk} - E_o) = 2 I_Q - I_{bm} \tag{31.2}$$

$$(E_{ck})_Q = \left[V'_c - E_{bb} + I_Q/g_p \right] /\mu \tag{31.3}$$

$$E_s = E_o + (E_{ck})_Q - 0.5 \tag{31.4}$$

Eliminating I_Q between first and second equation one has

$$g_p(E_{bb} - V'_{bk}) - I_{bm} = E_o(2\,G_L + g_p)$$

From this equation, if E_{bb} and G_L are given, one has

$$E_o = \frac{g_p(E_{bb} - V'_{bk}) - I_{bm}}{2\,G_L + g_p} \tag{32}$$

and if E_{bb} and E_o are given one has

$$G_L = \frac{g_p\,(E_{bb} - V'_{bk} - E_o) - I_{bm}}{2\,E_o} \tag{33}$$

The maximum possible value of E_o for given E_{bb} occurs when $G_L = 0$ and is

$$(E_o)_{max} = E_{bb} - V'_{bk} - I_{bm}/g_p. \tag{34}$$

On the other hand, when $G_L \neq 0$, the maximum possible value of E_o is

$$(E_o)_{max} = (I_{kM} - I_{bm})/2\,G_L \tag{35}$$

according to eqs. (31.2) and (32).

As an example, given a 6J5 with $E_{bb} = 200$ V, $G_L = 10^{-3}$ mhos there follows

$$E_o = 9.65 \text{ V}$$

$$I_Q = 10.15 \text{ mA}$$

$$(E_{ck})_Q = -9.7 \text{ V}$$

The maximum possible value of E_o for the given value of G_L is 9.75 V; the maximum value of E_o for $G_L = 0$ is 156.2 V.

An interesting problem is the determination of the optimum value of G_L for maximum power output. One has

$$P_L = G_L E_c^2/2 = \frac{G_L}{2\left[2G_L + g_p\right]^2}\left[g_p\,(E_{bb} - V'_{bk}) - I_{bm}\right]^2$$

and letting $\frac{dP_L}{dG_L} = 0$ there follows

$$2\,G_L = g_p \tag{36}$$

which is the same result that applies for grounded cathode amplifiers.

III. D-C Cathode Followers

A typical circuit for the d-c cathode follower amplifier is indicated in Fig. MRI-14278-b. For generality it has been assumed that $E'_{bb} \neq E''_{bb}$.

One of the conditions of the design is that the cathode be at ground potential. Correspondingly one has

$$E_Q = E'_{bb} \qquad I_Q = G_k\,E''_{bb} \tag{37}$$

By application of Thevenin theorem the circuit of Fig. MRI-14278-b can be modified into that of Fig. MRI-14279a, with

$$G' = G_k + G_L\,, \quad E' = \frac{G_k\,E''_{bb}}{G_k + G_L} \tag{38}$$

The latter circuit is equivalent to that of Fig. MRI-14279b which is similar to the circuit of an a-c cathode follower having zero load admittance G_L.

The limit conditions of operation are

$$E_{ck} \leqslant E_{ck\ max} = -0.5\ \text{V}$$

$$I_Q = G_k\,E''_{bb} \leqslant (I_{kM} + I_{bm})\,/2 \tag{39}$$

$$P_p = E'_{bb}\,I_Q \leqslant P_{p\ max} \tag{40}$$

The design equations are

$$E'_{bb} = E_o + V'_{bk} + \frac{I_{bm}}{g_p} = V'_{bk} + E_o \left(1 + \frac{2(G_k + G_L)}{g_p}\right) \qquad (41)$$

$$I_Q = \frac{1}{2}\left[I_{bm} + g_p\left[E'_{bb} - V'_{bk} - E_o\right]\right] \qquad (42)$$

$$I_Q = I_{bm} + E_o\,(G_k + G_L) \qquad (43)$$

$$(E_{ck})_Q = \left[V'_o - E'_{bb} + I_Q/g_p\right] / \mu \qquad (44)$$

$$E_s = E_o + (E_{ck})_Q - 0.5 \qquad (45)$$

In general E_o and G_L are prescribed and the purpose of the design is to choose a convenient tube and evaluate E'_{bb}, E''_{bb} and G_k.

The choice of the tube is determined by the maximum voltage output E_o that it can deliver in accordance with the limitations (39) and (40). The upper limit of E_o is obtained letting G_k approach zero. Combining eqs. (39) and (43) one finds

$$(E'_o)_{max} = \frac{I_{kM} - I_{bm}}{2G_L} \qquad (46)$$

On the other hand combining eqs. (40), (41) and (43) one has

$$\left\{E_o\left(1 + \frac{2(G_k + G_L)}{g_p}\right) + V'_{bk}\right\}\left[E_o\,(G_k + G_L) + I_{bm}\right] \leqslant P_{pM}$$

wherefrom there follows

$$(E_o'')_{max} \simeq \frac{-V_{bk}'}{2\left(1 + \frac{2G_L}{g_p}\right)} + \sqrt{\frac{g_p\, P_{pM}}{G_L(g_p + 2G_L)}} \qquad (47)$$

The lower of the values (46) and (47) should be larger than the required E_o.

After the tube has been selected one proceeds to evaluate E_{bb}'. The upper limit of E_{bb}' again is determined in accordance to the limitations (39) and (40). Combining eqs. (39) and (42) one has

$$E_{bb}' \leq \frac{I_{kM} - I_{bm}}{g_p} + V_{bk}' + E_o \qquad (48)$$

On the other hand, combining eqs. (40) and (42) one has

$$E_{bb}' \leq \frac{1}{2}\left(V_{bk}' + E_o - \frac{2I_{bm}}{g_p}\right) + \sqrt{\frac{1}{4}\left(V_{bk}' + E_o - \frac{2I_{bm}}{g_p}\right)^2 + \frac{2P_{pM}}{g_p}} \qquad (49)$$

In general the value of E_{bb}' is chosen in dependence of the available power supply, so that the limitations (48) and (49) are satisfied.

After the value of E_{bb}' has been determined, eqs. (42) and (43) provide respectively I_Q and G_K. Finally the value of E_{bb}'' is obtained from eq. (37) and the values of $(E_{ck})_Q$ and E_s are computed from eqs. (44) and (45) respectively.

For example let us consider the design of a d-c cathode follower with E_o = 8 V, $G_L = 10^{-3}$ mhos. For the tube 6J5 eqs. (46) and (47) provide respectively

$$(E_o')_{max} = 9.75 \text{ V} \qquad (E_o'')_{max} = 11.17 \text{ V}$$

Therefore the 6J5 is suitable for the present design. According to eqs. (48) and (49) the upper limit of E_{bb}' is the lower of the following ones:

$$E'_{bb} \leq 196 \text{ V} \qquad E'_{bb} \leq 214 \text{ V}$$

Let $E'_{bb} = 180$ V. Equation (42) now provides

$$I_Q = 9 \text{ mA}$$

Eq. (43) then gives

$$G_k = 0.06 \times 10^{-3} \text{ mhos}$$

Finally

$$E''_{bb} = \frac{I_Q}{G_k} = 150 \text{ V}$$

and

$$-(E_{ck})_Q = -4.0 \text{ V}, \qquad E_s = 11.5 \text{ V}$$

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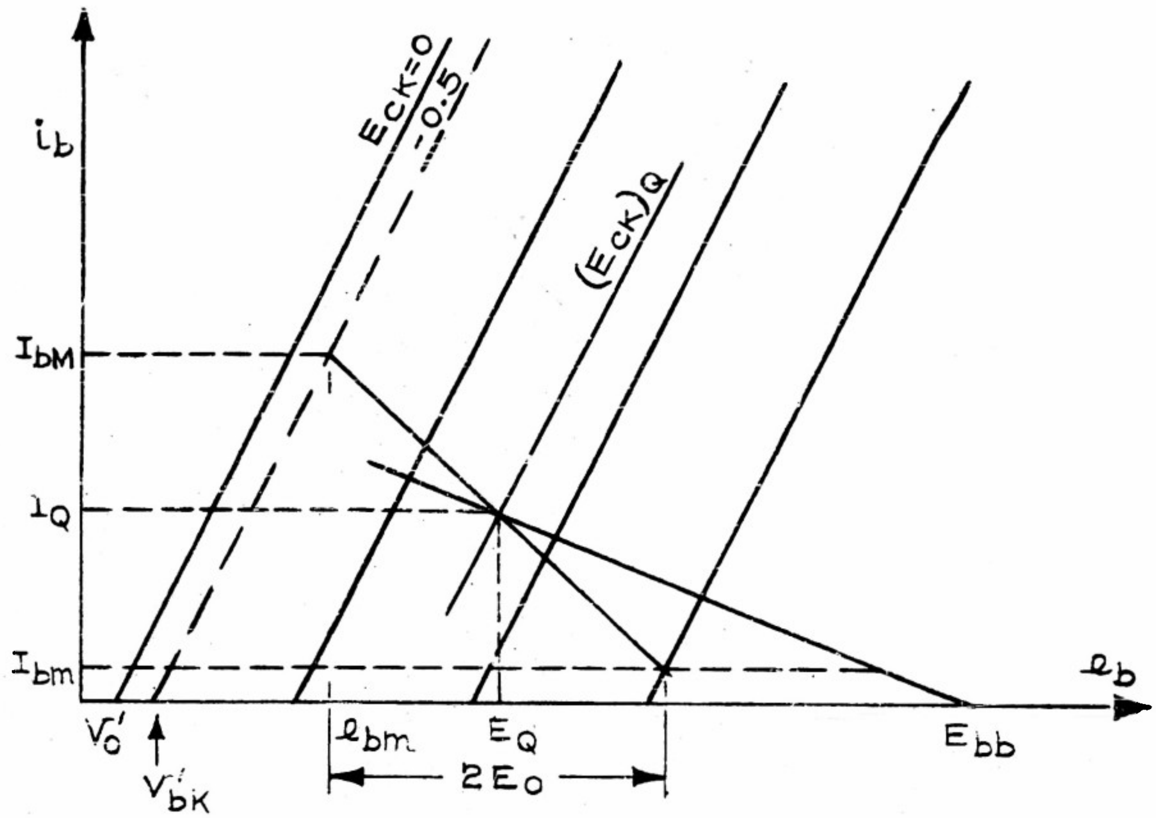
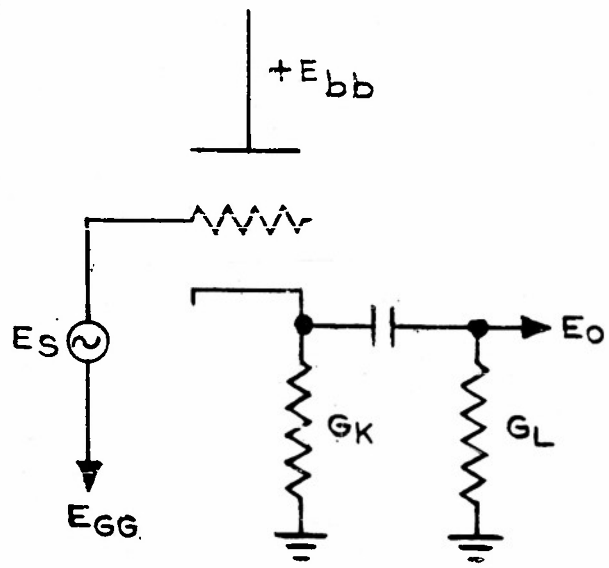


(a)- LINEARIZED PLATE CHARACTERISTICS OF A TRIODE VACUUM TUBE



(b)- A-C CATHODE FOLLOWER WITH CONDUCTIVE CATHODE ADMITTANCE

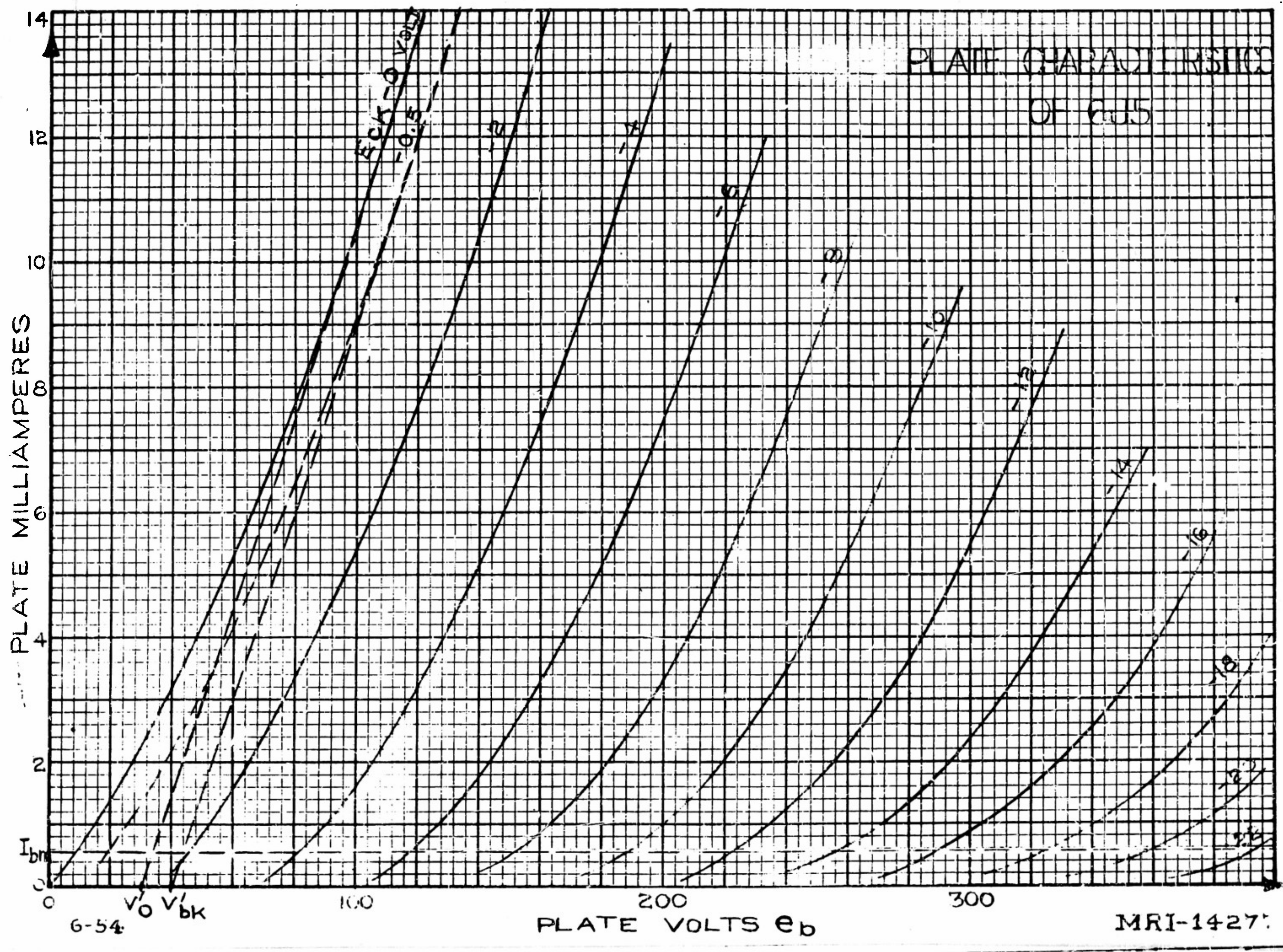
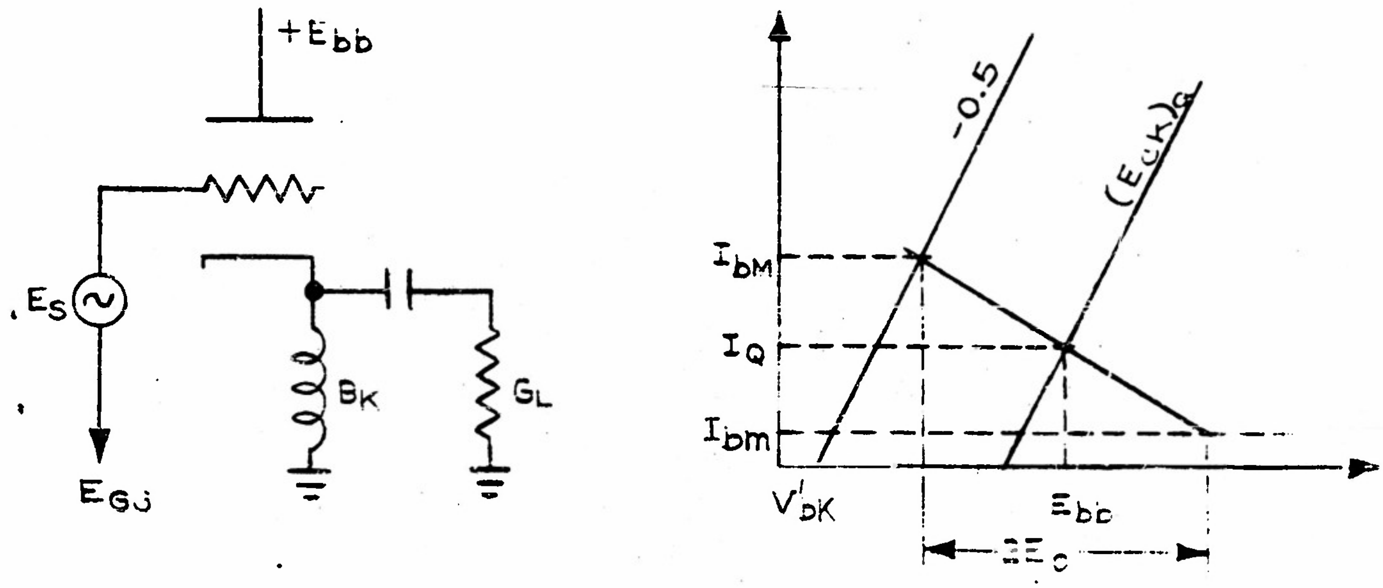
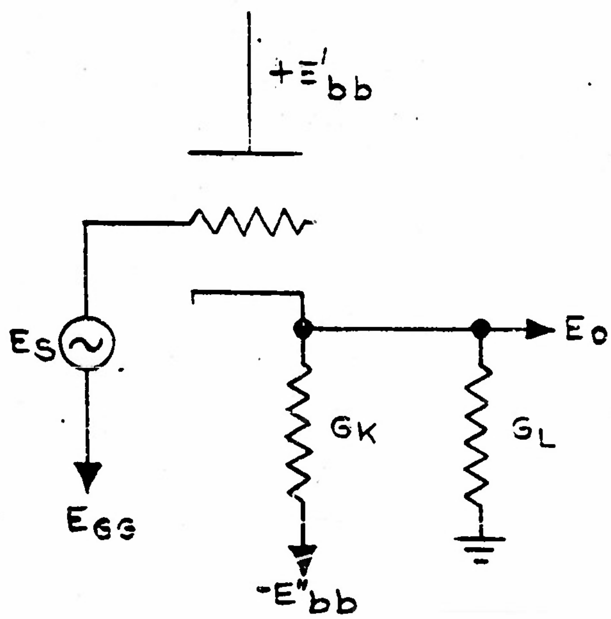


PLATE CHARACTERISTICS
OF 6J5
E_{CK} = 0 VOLT
-0.5
-2
-4
-6
-8
-10
-12
-14
-16
-18
-22
PLATE MILLIAMPERES
14
12
10
8
6
4
2
I_{bm}
0
100
200
300
V'_0 V'_{bk}
PLATE VOLTS e_b
6-54
MRI-14277

A-C CATHODE FOLLOWER WITH SUSCEPTIVE CATHODE ADMITTANCE

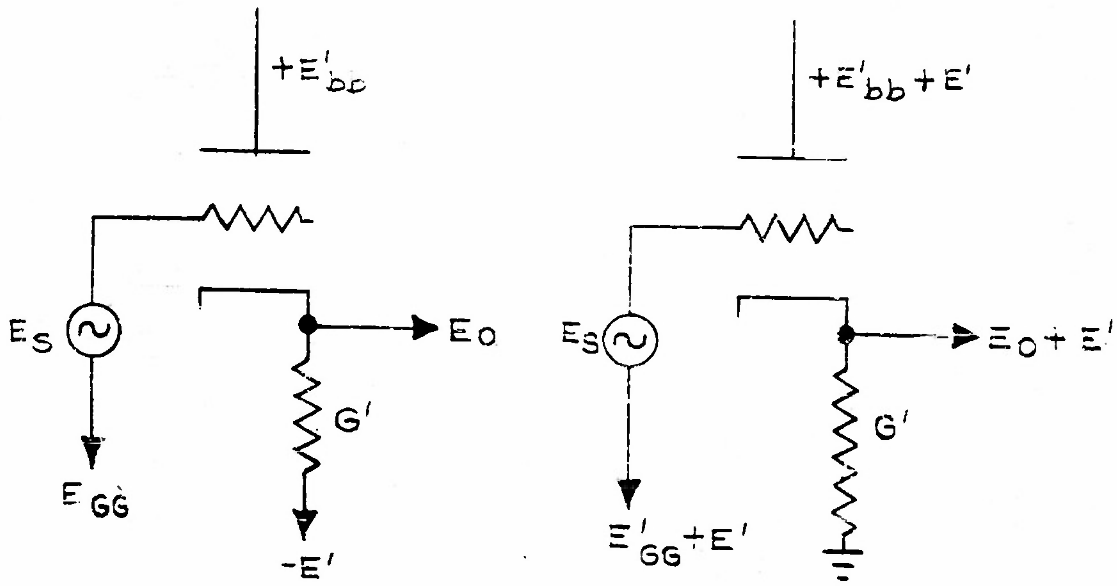


(a)



(b)

D-C CATHODE FOLLOWER



(a) (b)